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Integration of renewable energy in interconnected transmission grids

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Abstract

At modest penetration wind power merely substitutes electricity generated typically at thermal power plants and thereby only giving economic benefits comparable to the saved marginal fuel and operation and maintenance costs. At higher penetrations, it becomes increasingly important for the energy system to be able to operate without costly reserve capacity awaiting fluctuations in demand or wind power generation that need be countered.

Existing interconnections of transmission systems are mainly in order to assist in reducing reserve capacity in thermal power generation systems. While indeed relevant in thermal systems, this is typically even more so in renewable energy based systems, where fluctuations

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to a large extent are uncontrollable making interconnected systems an interesting option for integration of electricity produced on such energy sources.

Using a Danish example this article demonstrates how different demand and production patterns in different geographical areas assist in evening out fluctuations and imbalances between demands and productions in systems with high penetrations of renewable energy thereby reducing needs for reserve capacity. Prospects that will be relevant also in other places if renewables are to play a large role worldwide. However, the article also demonstrates that there are limits to what can be gained on this account.

Key words

Grid integration, wind power, interconnected transmission grids

Introduction

The transition from fossil fuel-based power generation to power generation based on fluctuating energy sources such as wind, sun, and wave power introduces challenging demands on the operation of electricity systems. Even without such constraints, other constraints in the form of cogeneration of power and heat, the cogeneration of power and cooling or the cogeneration of power and desalinated water impose problems on the systems' load-following capabilities. Development in the way electricity is being consumed adds another dimension to the issue. Traditional electric engines decrease their power up-take if generators are overloaded thus causing the frequency to drop and thereby relieving the generators of some load. With many electric engines operated through frequency-converters, loads are not relieved but rather kept constant.

The world has many trans-national grid interconnections – but also a number of systems disconnected from other systems or only connected via direct current (DC) lines and thus not synchronised and without the direct frequency controlled load balancing of interconnected alternating current (AC) systems. Scandinavia has one system (Nordel), most of continental Europe another (UCTE; after having been split up into two for a number of years following the wars in Balkan), North America has several. There are tendencies in the direction of larger interconnections, as exemplified with the Arab world. With the ongoing interconnection project *The Gulf Electricity Interconnection Grid*, a shift has been set in motion regarding changing electricity from being national or even local affairs to being a regional affair. Through the Gulf Electricity Interconnection Grid, the members of the Cooperation Council for the Arab States of the Gulf will eventually connect to the Mediterranean Middle East and Europe through Turkey as well as through the Arab-Maghreb line to North Africa and Spain. Though such distances are beyond what is readily technically feasible in terms of power exchange it does emphasize the interconnection trend of the larger area.

While the Gulf Electricity Interconnection Grid primarily is in order to reduce reserve capacity requirements as discussed by e.g. [1] and illustrated by the interconnection costs being distributed proportionally to the individual countries' reserve capacity savings, it will also have a positive effect on the possibility of exploiting renewable energy sources. Apart from most notably electricity production based on solid renewable fuels and hydropower, most renewable energy sources are characterised by intermittent natures and therefore an inherent need of either reserve capacity or other means of dealing with the fluctuations. In general, the smaller the system, the fewer the plants, the smaller the variation in energy sources and the smaller the geographic extension of the area in question, the larger the need

for reserve capacity. Interconnection schemes are therefore seen as measures required for integration of fluctuating renewable energy sources, see e.g. [2]

In line with the European Union's adoption of a stringent Kyoto-derived carbon dioxide emission reduction target, Denmark has pursued an ambitious energy policy. This has resulted in a complex energy system with many sources of energy being tapped and many interdependencies between sources, demands and conversion systems. In addition, however, Western Denmark has 1200 MW AC capacity to Germany, 1100 MW high voltage DC (HVDC) capacity to Norway and 600 MW HVDC capacity to Sweden while Eastern Denmark has a total capacity of 1900 MW to Sweden and 600 MW to Germany. Though not mutually connected (see figure 1), the two non-synchronised areas of Denmark thus each have strong ties abroad aiding in power balancing and reducing needs for reserve capacity. The Danish international connections are summarized in table 1.

In addition to the issue of mere generating capacity, an added issue is that of ancillary services (basically grid stability) which is getting increasing attention within utilities and the research community addressing the integration of fluctuating electricity sources. This is increasingly important as these services traditionally have been supplied by the large power plants and with stronger reliance on distributed generation technologies, the systems must maintain resilience against grid disturbances without needing these ancillary service providers of the past.

Scope of article

The scope of this article is to analyse how reserve capacity is required in the Western Danish electricity system. The analyses are made under different assumptions regarding the variation

curves of supply and demand as a consequence of areas being interconnected or not and under different assumptions of developments in installed wind power capacity; wind power being the most notable fluctuating power source in Denmark.

Time variations of demands and productions

Both production and consumption varies in a diurnal cycle, a weekly cycle and a seasonal cycle. The diurnal cycle of the demand is due to the timing of meal preparation, industrial activity, need for illumination etc. The weekly demand cycle is due to the reduced needs of weekend-closed companies, institutions and organisations and the seasonal demand cycle due to changing needs for illumination, heating and cooling at high latitudes.

The production system has to follow the demand variations, so neglecting international trade, the production should equal the demand curve. In addition however, in systems exploiting renewable energy sources, cogeneration of heat power (CHP) or cogeneration of cooling and power, additional time variations are introduced. The CHP plant will e.g. have a production which is determined by temperature variations which vary in a daily and a seasonal cycle as well as with a stochastic element. The same applies to photo voltaic-based electricity generation where the altitude of the sun varies with the yearly cycle on top of which comes local climatic conditions influencing cloud coverage. The last to be mentioned here is wind power, which probably has the widest addressed fluctuations in power output of any generating technology. Depending on geographical setting, wind power may have a diurnal variation with a tendency of lower production at night than during the day as is the case in Denmark and a seasonal variation with generally higher wind velocities during the winter at the same time as the density of the air is higher thus adding to the power.

All these are factors contributing to the difficulty of designing energy systems with load following capabilities. One factor works against these fluctuations of which some are long-term foreseeable, some are short-term foreseeable and some are not foreseeable: geographic distribution of the production and the demand.

In figures 2 and 3 for instance, hourly wind power inputs for the two non-connected areas of Denmark are shown for a winter and a summer week respectively.

The two individual areas' variations are higher than for the two areas combined. For the entire year 2004 for instance, wind input in Western Denmark averaged 555 MW and in Eastern Denmark 195 MW. The average deviation from these averages were 411 and 148 MW respectively indicating the fluctuating nature of wind power. Scaling Eastern Denmark to the Western Danish average the 148 MW would correspond to 411 MW. However, adjoining the two areas and again scaling to the Western Danish average, the average deviation would fall to 400 MW. This is of course not sufficient to render a flat production curve but it does demonstrate how enclosing a larger geographic area adds stability to the production. Particularly when taking into account the relatively modest size of Denmark and the fact that due to its size, the two areas of the country are usually subjected to the same depressions and high pressures.

Demands in the two parts of Denmark are relatively similar though with a tendency of a lower demand in the Eastern part during the summer as indicated in figures 4 and 5. In order to gain a more even diurnal demand curve, larger geographic areas would need to be covered. Encompassing areas or countries with diverse industrial bases with different mixtures of

primary, secondary and tertiary economic sectors would even out demand peaks caused by large single users or clusters of similar and often partly synchronized industries. If it is habitual that certain types of industries work the same shifts in a country, then this aggravates the peaks. Covering more time zones in a demand area will also generate a natural alleviation of large power surges.

This is of course from an overall system perspective. Technical, economic or organizational bottlenecks may influence the extent to which the effects of geographic dispersion may be utilised.

Energy system scenario

The analyses in this article take their point of departure in an energy system scenario for the year 2020 used in analyses by the Danish Energy Authority ([5] and [6]). Demands are thus the expected with a continuation of present trends and policies. However, the amount of on-shore and off-shore wind capacity corresponds to the present level in spite of expected future increases in especially off-shore wind. Going even beyond the current level of approximately 20% wind share in Western Denmark, however would limit the extent to which the analyses and results would be relevant and valid in other countries.

Thermal power plants are modelled as three types; 1) locally controlled CHP plants supplying electricity to the grid as well as heat to district heating areas. 2) Centrally dispatched CHP plants and 3) centrally dispatched power plants operating in condensing mode i.e. only with electricity generation. These condensing mode plants are merely modelled present in adequate quantities.

Finally, a certain degree of heat humps are included to assist integration of the fluctuating wind resource. The main parameters of the energy systems scenario are listed in Table 2.

The core point of the analyses is of course to model the impact of adjoining areas and benefiting from the equalization of diurnal, weekly and seasonal variation curves. As noted regarding figures 4 and 5 however, demand variations are not so large, so mainly the impact of the wind variations are modelled here. This is done by comparing the energy system response to

- A. applying the actual wind generation of a year on an hourly basis (Denoted Reference) with
- B. applying an artificial wind generation of a year on an hourly basis averaging the actual data from the two areas where the smaller Eastern Area is weighed to match the Western level (denoted Artificial)

In one analysis, however, demand is modelled applying an artificial demand curve averaging the actual demand curve and the same curve shifted six hours as an indication of the response of the system to a drastic geographic equalisation and a large interconnection of grids.

The main analyses are furthermore conducted with two different regulation strategies in which the local CHP plants are operated

- A. according to a heat demand (Regulation Strategy 1) and
- B. in order to best help keep overall electricity load balance while also furnishing the required heat (Regulations Strategy 2)

In order to model the response of systems without the Danish heat-tied production and thus in order to obtain results valid for other climates, the system is then modelled in

- A. a situation with the CHP-tied heat demand that is applicable mainly in temperate and cold climates.
- B. a situation without the CHP-tied heat demand

Finally, the system is modelled with higher quantities of wind power corresponding to levels twice and triple the present level.

The energy system is modelled using the input-output model EnergyPLAN model developed by Henrik Lund (see e.g. [7] & [8]) which is a model designed to make analyses of energy systems with high degrees of fluctuating power and heat sources and many interdependencies of the energy systems. The parameter used for assessing the energy system performance is the required level of electricity generation in condensing mode operation as this has the lowest overall thermodynamic efficiency and therefore should be avoided.

Results of energy systems analyses

Modelling the energy system reveals that average production on condensation based power plants is decreasing slightly using the artificial wind distribution compared to using the actual wind distribution of the Reference situation. This applies to Regulation Strategy 1 and 2 as well as for the situation without any heat demand and CHP generation as indicated in figure 6 showing the changing needs for condensing mode power generation. In fact, however, as it also evident from the results in figure 6, differences are small and change over the year.

In some months – notably spring months with negative values in the graphs - the reference wind distribution curve proves better than artificial wind distribution curve indicating that the actual wind distribution in fact matched demand better. For the entire year, average condensation-based power generation does nonetheless decrease by 7-8 MW by adopting the more levelled wind power distribution curve. Although limited, it does indicate some prospects particularly taking into consideration that the marginal electricity production typically is at older and less fuel-efficient plants.

Showing the results in the form of a duration curve for condensation-based power generation as in figure 7 demonstrates the same marginal shift to the left from applying the artificial wind distribution curve for a larger geographic area. It also shows the duration curve in case wind power gave a fixed input for comparison. This corresponds to evening out wind variation over a very large area. Even in this case, condensation-based power generation would increase at points as was also evident from figure 6. The reason of course being that with fluctuating wind power, wind variations will follow demand at times.

Modelling a system with a demand curve which has been smoothened corresponding to an equalization over six time zones, renders a duration curve shifted slightly left (not included in article).

Without heat demand tying CHP heat production and thus CHP electricity generation, condensing mode electricity generation naturally increases as shown in figure 8, and with the artificial variation curve of wind power applied, demands are marginally lower.

These results are expected as CHP has a much larger share of power generation than wind turbines and the influence of omitting heat generation and thus CHP generation is therefore larger than the influence of going between two different sets of annual wind power variation curves.

Assuming a higher penetration of wind power, results with the actual reference wind distribution and with the constructed artificial wind distribution diverge more as illustrated in figure 9 showing results for the energy system assuming double and triple the amount of wind power presently available. Here applying the more level artificial distribution curve for wind reduces correspondingly higher shares of electricity generation in condensing mode operation.

One apparent element in figure 9 deserving a comment is the fact that high wind (as illustrated by the triple curve) may require a higher level of electricity in condensing mode operation. This is due the present circumstance that wind turbines do not actively assist in maintaining grid stability – i.e. frequency stability, voltage stability and in supplying adequate short-circuit power available. At high levels of instantaneous wind production, other power plants – typically large CHP plants or condensing mode plants using synchronous generators - need to generate a correspondingly higher output to supply the required ancillary services.

If ancillary services were supplied from wind turbines, the duration curves in figure 9 would shift to the left and have a steeper inclination. This is shown in Figure 10 where the wind turbines are modelled being able to supply ancillary services.

Error analysis and validation of results

The analyses have been made using the EnergyPLAN model. Having been applied to a number of energy systems analyses published in peer-reviewed journals, the model itself is well-published and also well-documented in literature. The model determines the optimal functioning of the energy system based on a number of exogenous characteristics. These include electricity and heat demand patterns and production on weather and climate given production units e.g. wind power. Based on these user-given variations and other systems characteristics such as storages and regulations strategies, the model determines what other productions must be scheduled to assure power balance in the system.

As the model is deterministic rather than probabilistic, the time variation play an important role in the modelling. s potential source of error in the analyses is hence the fact that the analyses are carried out with wind production data for a specific year. In order to asses the influence on this, a second set of data for 2005 have been used in the key analysis of the immediate influence of interconnection – i.e. a comparison of required condensing mode generation with a) actual wind variation of the year and with b) artificially levelled wind variation. Here the results show also a marginal decline in average condensing mode power generation. While it is 8 MW with 2004 data, the decline is only 2 MW with 2005 data. There is thus still a positive albeit marginal positive influence.

Conclusions

The results of this article demonstrate that increasing the geographical extension of the area in which renewable fluctuating energy sources are being exploited reduces the average need for reserve capacity in the form of power plants operating in condensing mode operation. While the analyses have focused on one single source of renewable energy i.e. wind power,

the analyses indicate that analyses of energy systems encompassing more unrelated energy sources or areas with larger geographic distributions would lower the demand for reserve capacity further. This is thus also the result of interconnecting transmission areas with distinct production or consumption patterns.

However, the results also show that while there is something to be gained in terms of improving the integration of wind power by expanding the geographic area of grid interconnection, grid interconnection cannot stand alone. While average condensing mode capacity requirement does drop, the same is not generally the case with the maximum required condensing mode capacity. Other measures are hence required to facilitate the integration of fluctuating renewable energy. Such other measures have not been addressed in this article though.

In terms of integrating renewable energy sources, the result also demonstrate that concern for ancillary services must be a priority as this can otherwise impede transition to renewable energy sources if conventional thermal power plants need to supply these.

Acknowledgements

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References

[1] Bowen BH, Sparrow FT, Yu Z, Al-Salamah M. Policy analysis in the development of integrated Middle East regional energy markets In Proceedings of 8th International Power Generation Conference, Dubai, October 7-9, 2002

[2] Matthews J. Seven steps to curb global warming. Energy Policy 2007; 35(8): 4247-4259

[3] Energinet.dk. Foreign connections (Udlandsforbindelser). Fredericia 2007 (In Danish).

See also

<http://www.energinet.dk/da/menu/Transmission/Udlandsforbindelser/Udlandsforbindelser.htm>

[4] Energinet.dk. Extraction of market data (Udtræk af markedsdata). Fredericia 2007. (In Danish). See also

<http://www.energinet.dk/da/menu/Marked/Udtræk+af+markedsdata/Udtræk+af+markedsdata.htm>

[5] Danish Energy Agency. Report from the workgroup on electricity production form CHP and RES. (Rapport fra arbejdsgruppen om kraftvarme og VE-elektricitet). Copenhagen 2001 (In Danish). See also

http://www.ens.dk/graphics/Publikationer/Forsyning/Eloverlobsrapport_11-10-01.pdf

[6] Danish Energy Agency. Attachments to report from the workgroup on electricity production form CHP and RES, Attachment 6 (Rapport fra arbejdsgruppen om kraftvarme og

VE-elektricitet. Bilagsrapport). Copenhagen 2001 (In Danish). See also

http://www.ens.dk/graphics/Publikationer/Forsyning/Bilag_eloverlob_16-10-01.pdf

[7] Lund H. Münster E. Tambjerg LH. EnergyPlan – Computer model for energy system analyses Version 6.0. Aalborg University 2004. See also

[8] Lund H. Duić N. Krajac̃ić G. da Graça Carvalhoc M. Two energy system analysis models: A comparison of methodologies and results. Energy 2007; 32 (6): 948-954

Figure captions

Figure 1: The 400 kV transmission grid in Denmark and connections abroad. Western Denmark is AC connected to Germany while Eastern Denmark is AC connected to Sweden and the two areas are thus not synchronized.

Figure 2: Wind power generation in Eastern and Western Denmark a winter week in 2005. The abscissa is in absolute hours of the year. Values for Eastern Denmark have been scaled so the half-year average matches that of Western Denmark. Data source: [4]

Figure 3: Wind power generation in Eastern and Western Denmark a summer week in 2005. The abscissa is in absolute hours of the year. Values for Eastern Denmark have been scaled so the half-year average matches that of Western Denmark. Data source: [4]

Figure 4: Electricity demand in Eastern and Western Denmark a winter week in 2005. The abscissa is in absolute hours of the year. Values for Eastern Denmark have been scaled so the half-year average matches that of Western Denmark. Data source: [4]

Figure 5: Electricity demand in Eastern and Western Denmark a summer week in 2005. The abscissa is in absolute hours of the year. Values for Eastern Denmark have been scaled so the half-year average matches that of Western Denmark. Data source: [4]

Figure 6: Change in average monthly condensation-based power generation with the artificial yearly wind distribution curve with Regulation Strategies 1 and 2 and in a situation without any heat demand covered by CHP. Positive values indicate reduced condensation-based power generation compared to the reference scenario with the actual wind distribution.

Figure 7: Duration curve for the reference system and for system with artificial annual variation curve for wind power and a system with constant wind power of 550 MW throughout the year.

Figure 8: Duration curve for the reference system, for a system without heat-tied CHP generation with the same reference wind variation curve and the same with the artificial annual variation curve for wind power.

Figure 9: Duration curve for the reference system and for system with double and triple the amount of wind power with 2004 and artificial annual wind variation curves for wind power.

Figure 10: Duration curve for a) the reference system b) for a system with triple the amount of wind power using reference wind distribution and c) for a system with triple the amount of wind power using reference wind distribution and where wind turbines are enabled to supply ancillary services

Tables

Connection	Capacity	Type of connection
W Denmark – Germany	1200 MW	Aerial AC lines (400, 220 & 150 kV)
W Denmark – Sweden	600 MW	Underwater HVDC lines (250kV) – <i>KontiSkand</i>
W Denmark – Norway	1100 MW	Underwater HVDC lines (250 & 350 kV) – <i>Skagerrak</i>
E Denmark – Sweden	1900 MW	Underwater AC lines (400 & 132 kV)
E Denmark – Germany	600 MW	Underwater HVDC line (400 kV) - <i>Kontek</i>

Table 1: Foreign electric connections from Denmark. Source: [3]

Consumption	Generating capacity	
[TWh]	[MW]	
24.87 Electricity	1450	Locally controlled CHP
20.00 District heat	1300	Centrally dispatched CHP
	5000	Central stations – Condensing operation
	2400	Wind (inland and off-shore)
	350	Heat pumps

Table 2: Energy system scenario parameters.

Figure 1

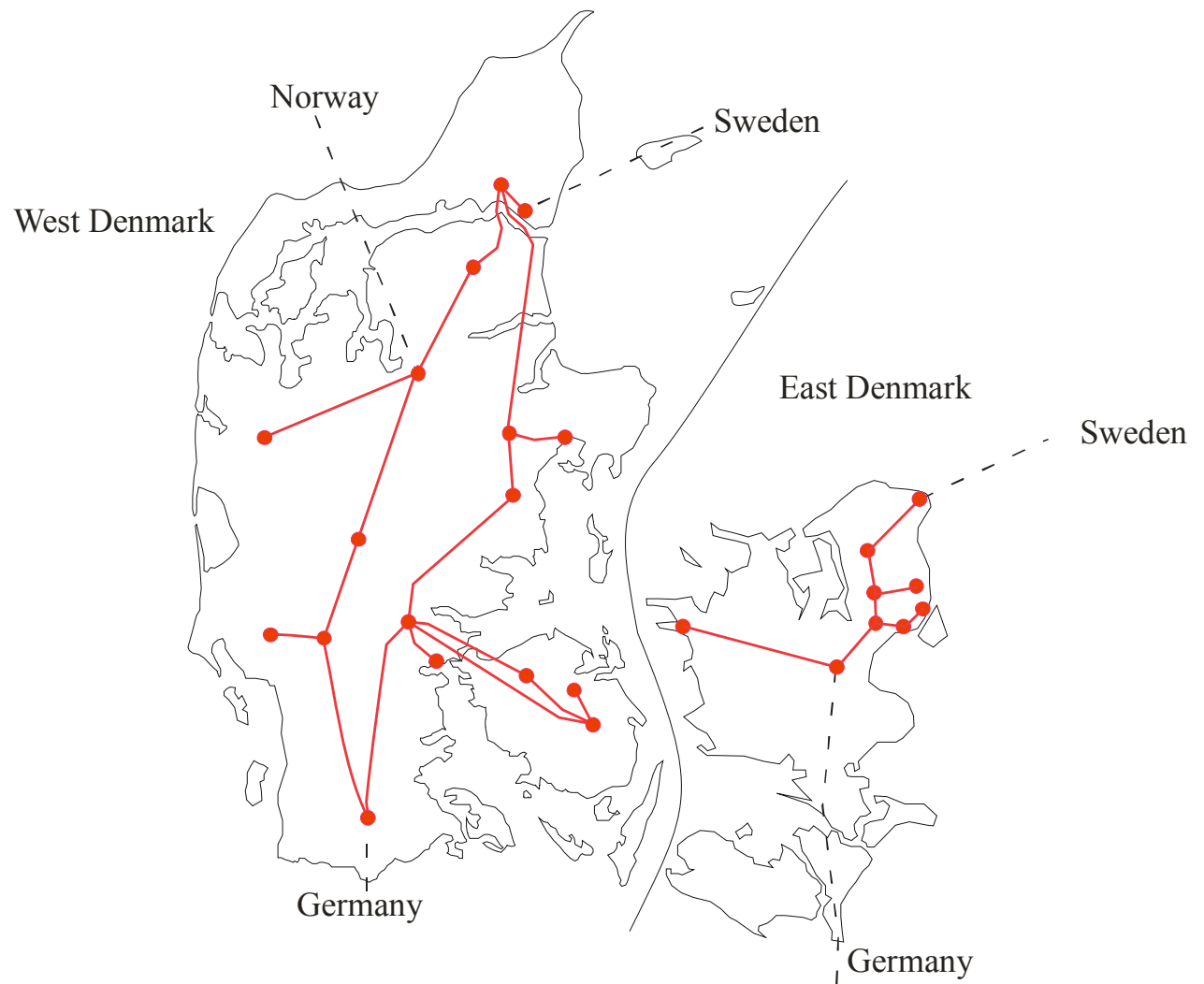


Figure 2

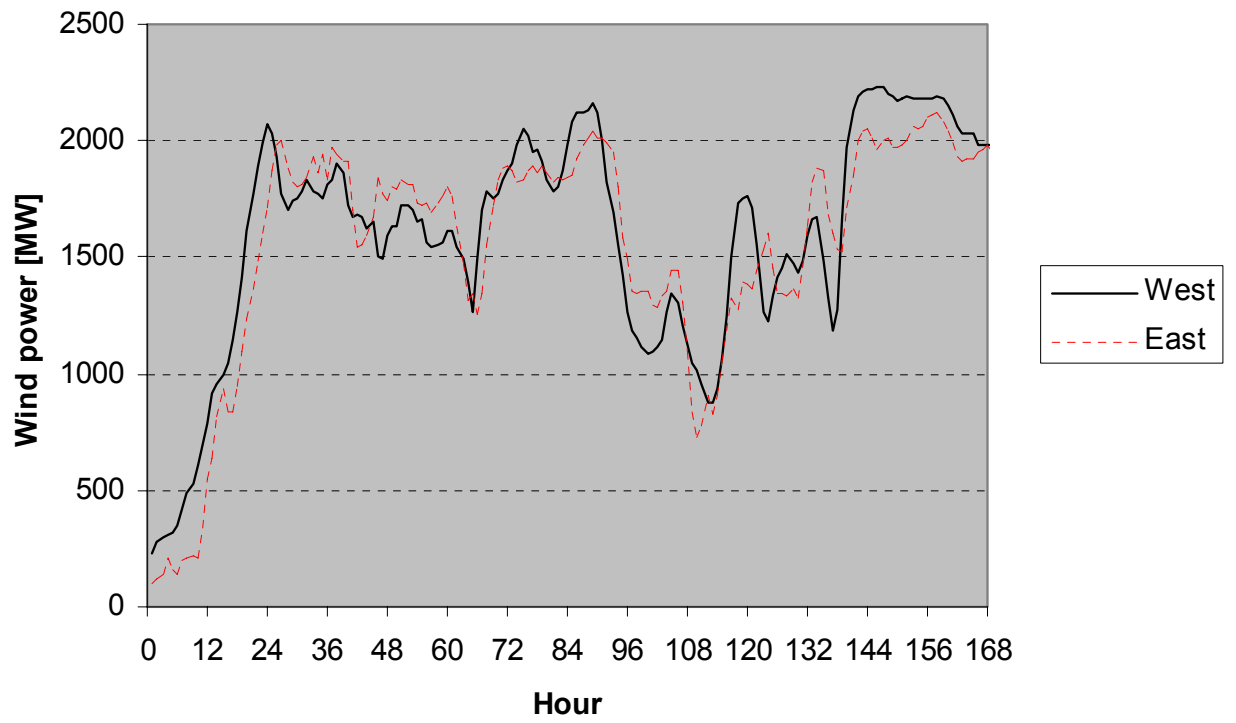


Figure 3

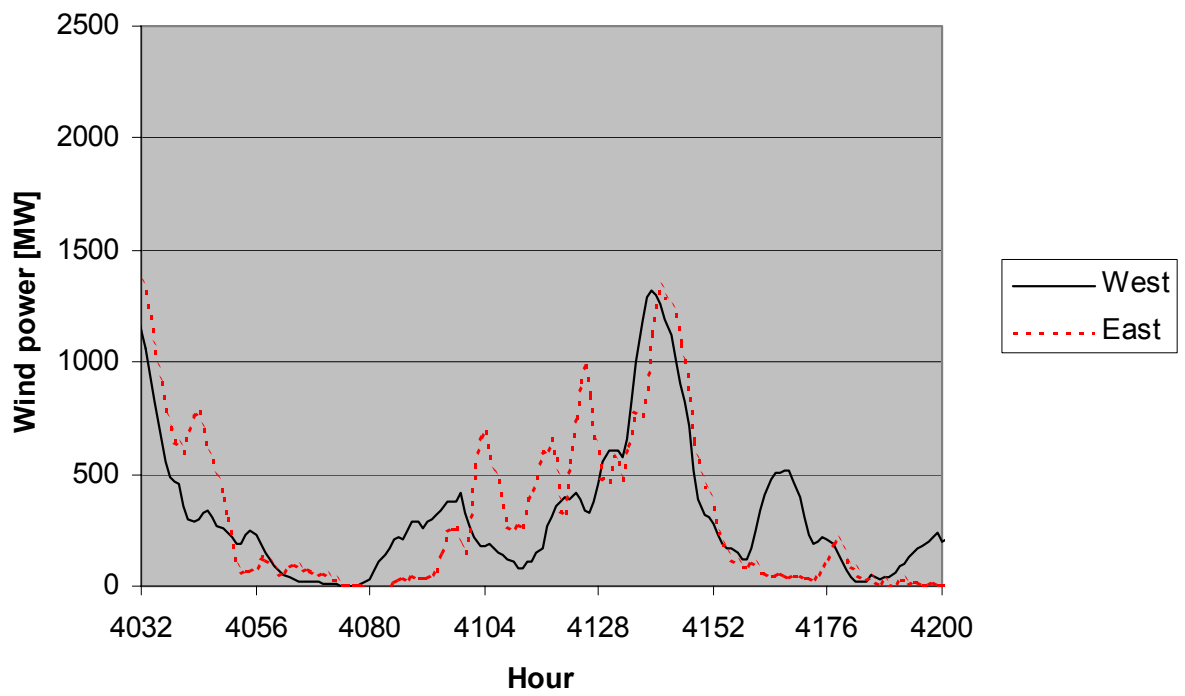


Figure 4

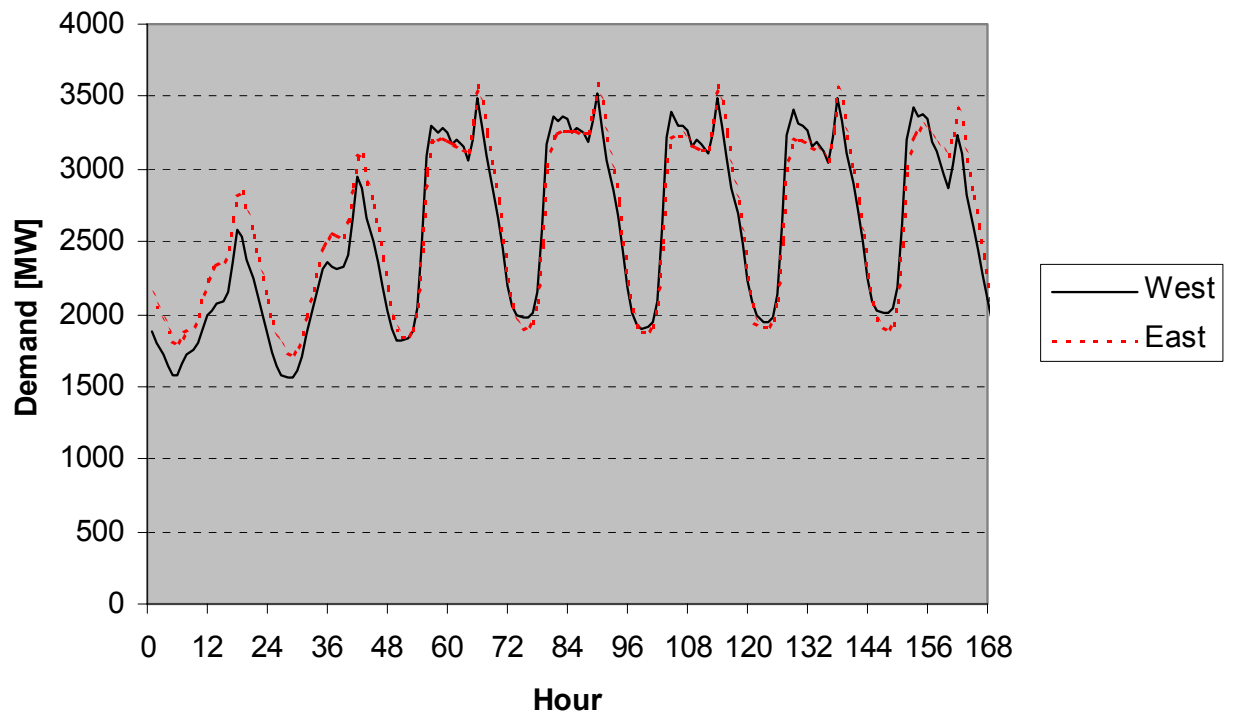


Figure 5

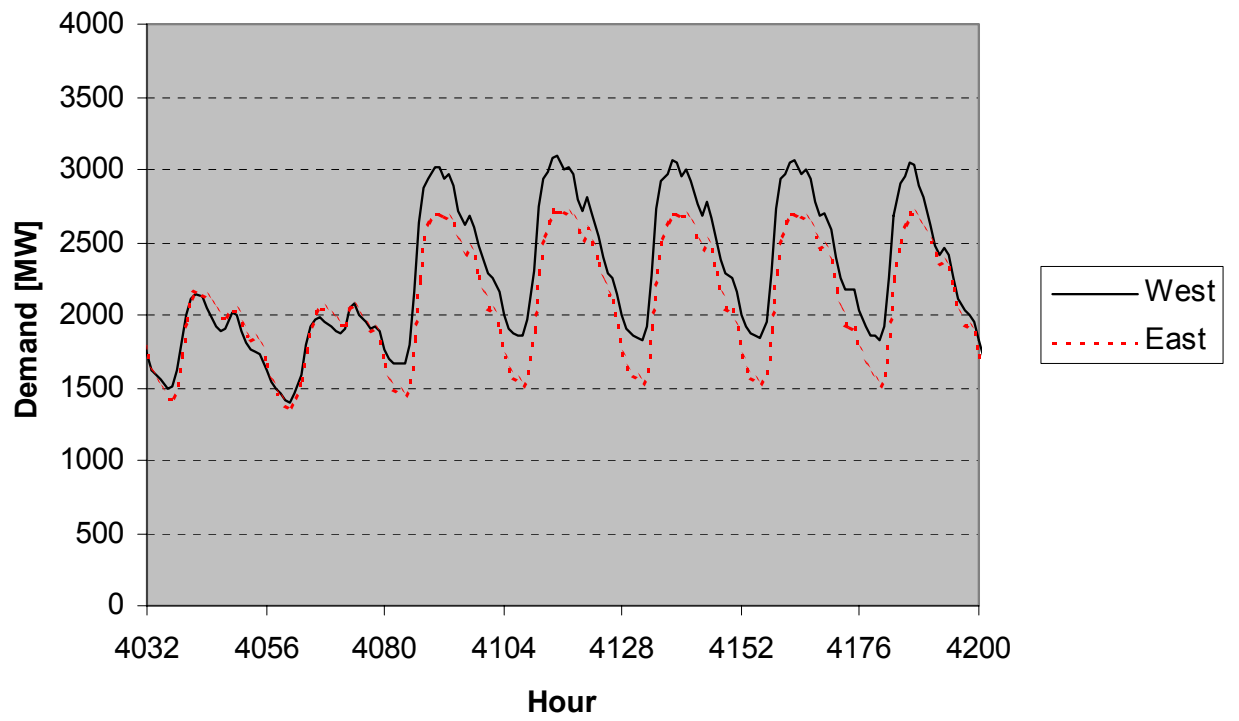


Figure 6

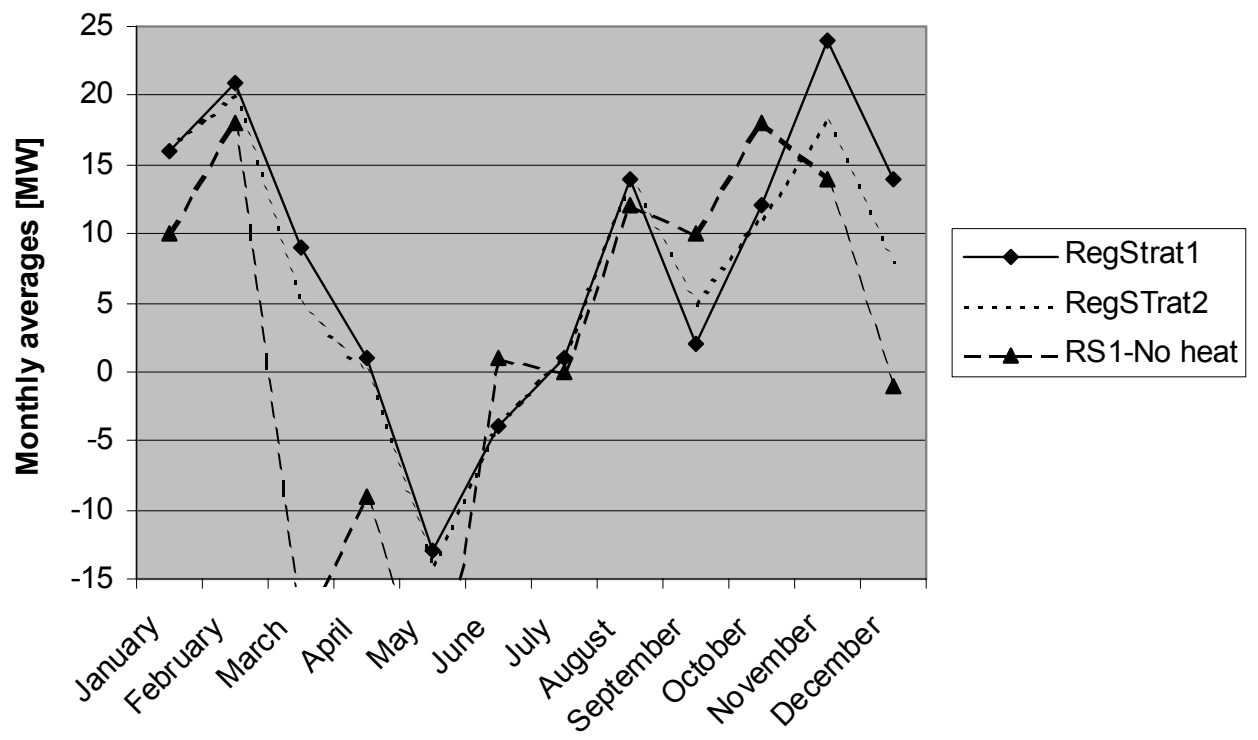


Figure 7

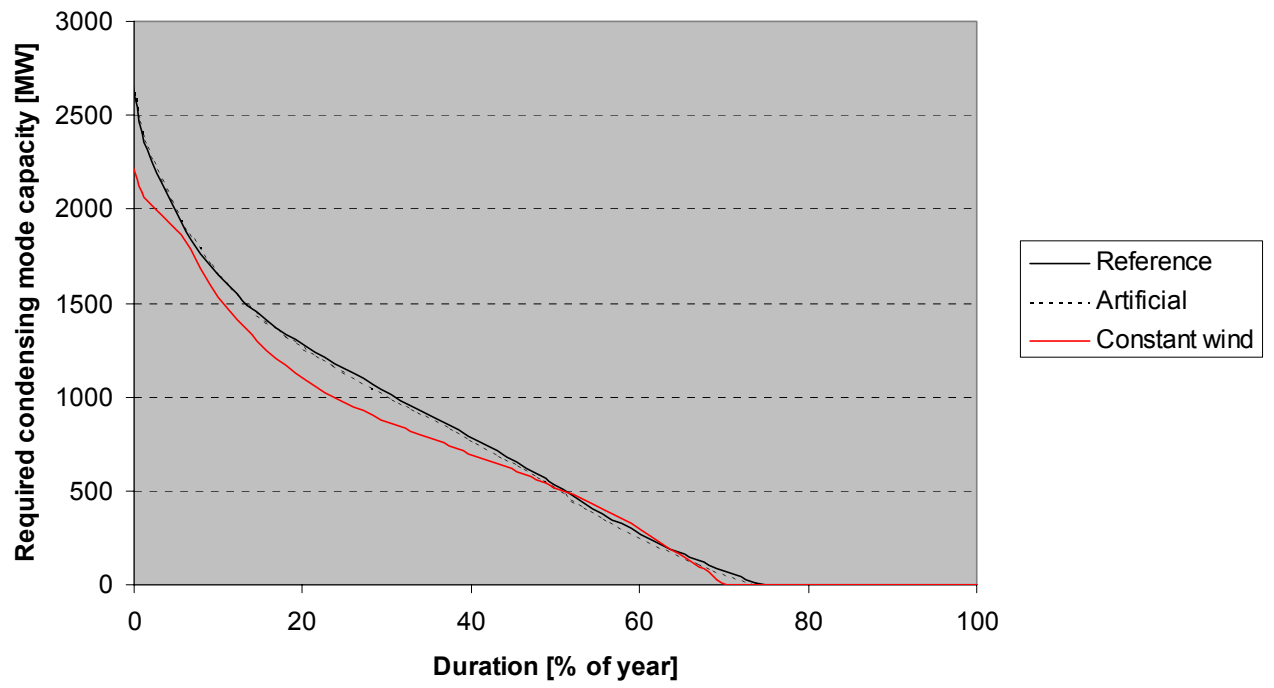


Figure 8

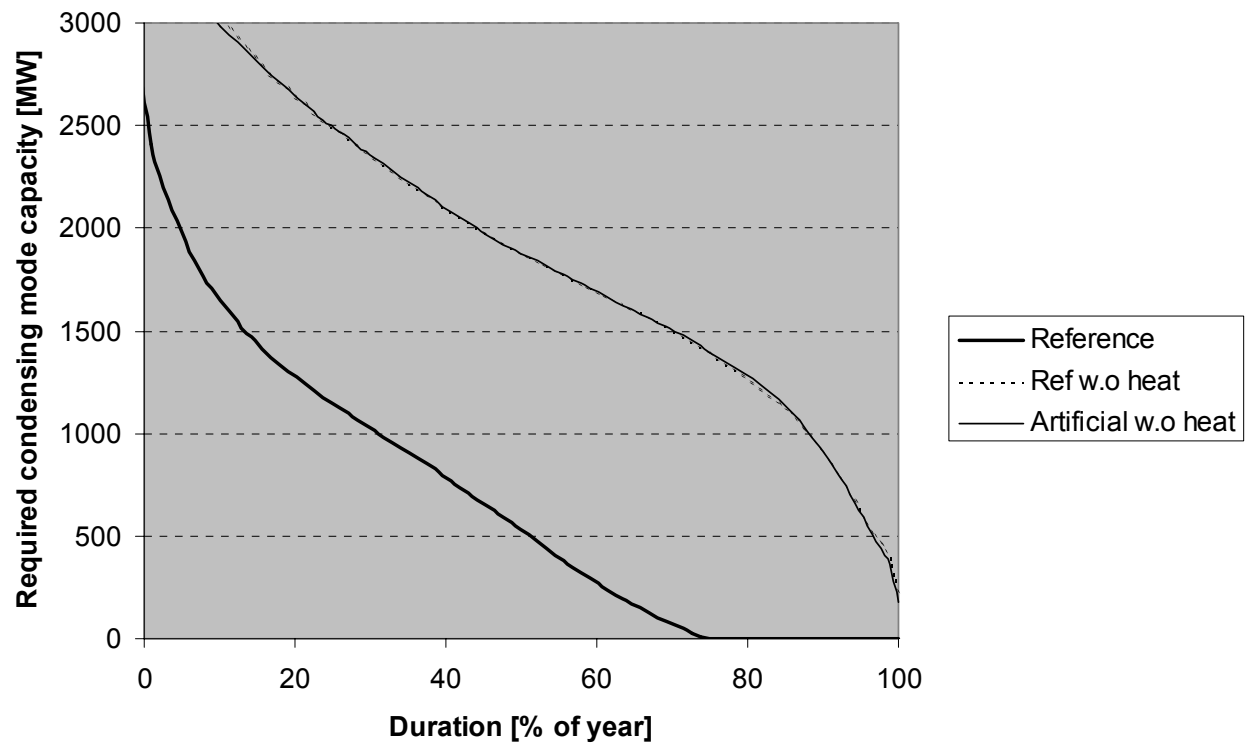


Figure 9

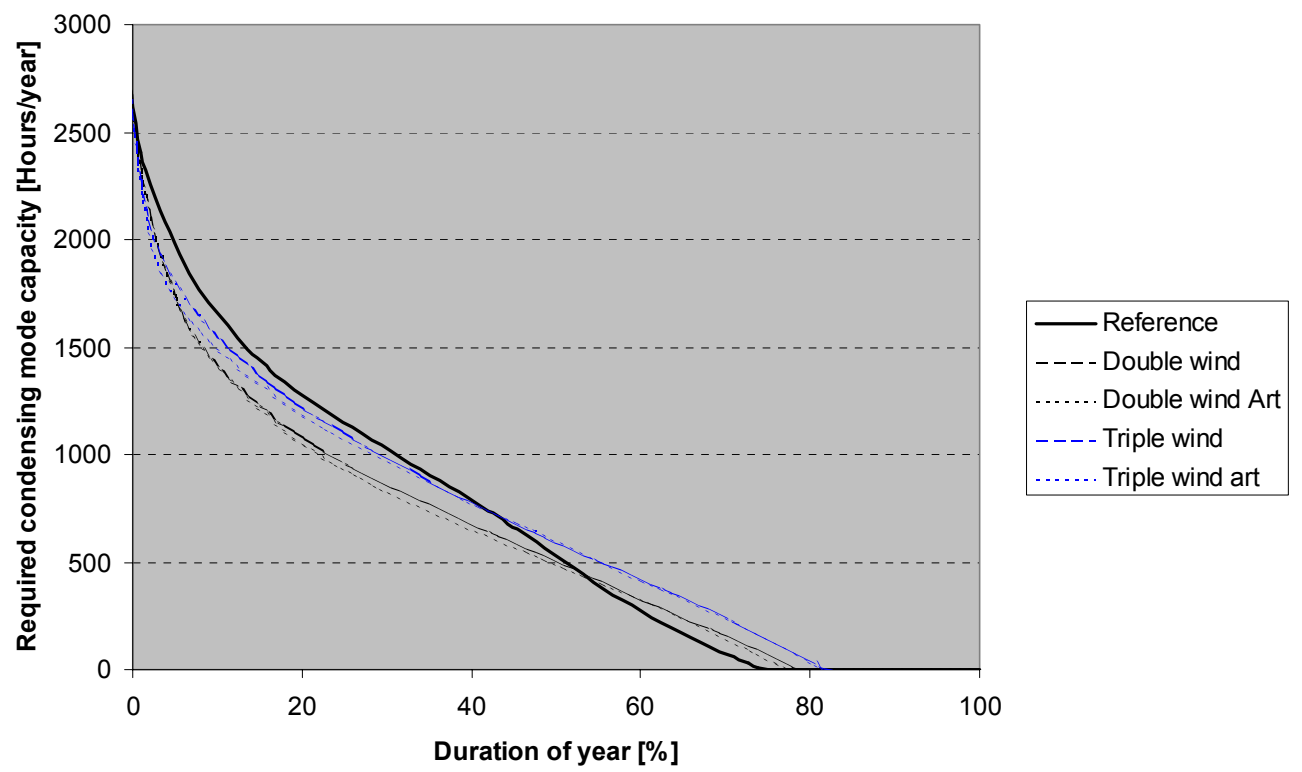


Figure 10

